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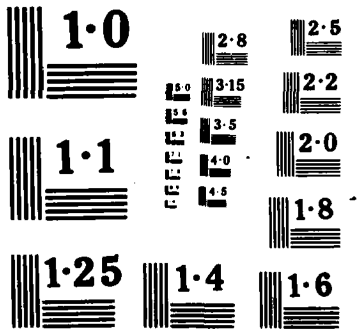
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Two dense plasma focus systems, the hypocycloidal-pinch and the Mather-type, were investigated as the potential excitation light sources for high energy, short-wavelength lasers. Using the hypocycloidal pinch (HCP), extensive lasing experiments were successfully performed, for the first time, on organic dyes producing results indicative of the capabilities and limitations of the HCP system as an optical pump. A proof-of-principle lasing experiment was also performed for the first time using the Mather-type dense palsma focus (MDPF) sucessfully. Results thus far indicate that both HCP and MDPF are excellent high-energy, short-wavelength optical pumps and that as an optical pump, the MDPF system is more versatile, efficient, and powerful than the HCP system, especially in the short-wavelength spectral region.

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Final Technical Report prepared for AFOSR

by

KYEKYOON (KEVIN) KIM

CHARGED PARTICLE RESEARCH LABORATORY
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
UNIVERSITY OF ILLINOIS
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ABSTRACT

Two dense plasma focus systems, the hypocycloidal-pinch and the Mather-type, were investigated as the potential excitation light sources for high-energy, short-wavelength lasers. Using the hypocycloidal pinch (HCP), extensive lasing experiments were successfully performed, for the first time, on organic dyes producing results indicative of the capabilities and limitations of the HCP system as an optical pump. A proof-of-principle lasing experiment was also performed for the first time using the Mather-type dense plasma focus (MDPF) successfully. Results thus far indicate that both HCP and MDPF are excellent high-energy, short-wavelength optical pumps and that as an optical pump, the MDPF system is more versatile, efficient, and powerful than the HCP system, especially in the short-wavelength spectral region.

I. SUMMARY

Two dense plasma focus systems, generally known as the hypocycloidal pinch (HCP) and the Mather-type dense plasma focus (MDPF), were investigated to determine their capabilities and limitations as new high-energy, short-wavelength optical pumps.

Detailed dynamic and spectral studies of the HCP plasma light were performed indicating that control of the plasma luminescence is achieved by the choice of gas, its fill pressure, and the capacitor bank voltage and its stored energy. The rise time of this "plasma flashlamp" depends mainly on the gas species, the fill pressure, and the inductance of the capacitor bank discharge circuit. By using the HCP plasma as the excitation light source, laser activities were obtained for the first time from organic dyes. Output laser energy of approximately 2 mJ per cm^3 of lasing medium, or 2 kW/cm^3 for a 1-μs laser pulse, was obtained from rhodamine 6G, courmarin 480, LD 490, and coumarin 504 dyes. That both the coumarin 480 and rhodamine 6G lasers have comparable output power is significant in that it is a direct proof that the HCP light source is more efficient than the commercial xenon flashlamps in pumping lasers in the blue-green spectral region.

The investigation of MDPF as yet another new optical pump was initiated as an effort to utilize all the advantages of HCP but to eliminate the features that are considered to be an impediment in developing HCP as the most efficient plasma-light optical pump. MDPF was chosen for the following reasons: First, the MDPF light makes possible an easy installation of light reflectors which can efficiently direct the plasma light toward the lasing medium. Second, unlike the case of HCP, there is no danger that the presence of the lasing medium will interfere with the plasma focus formation. Therefore, a longer lifetime is expected of MDPF at high energies. Third, the x-ray output of the MDPF device is generally considered to be the highest of

all the plasma compressors currently put to use as an optical pump, thus making MDPF a more versatile short-wavelength excitation light source.

By operating an MDPF as an optical pump, for the first time since its advent in 1964, laser activities were successfully achieved. Rhodamine 6G dye was used as the lasing medium, producing a laser pulse 1 μs in duration the more than 50 kW in output power.

A. Technical Objective

The specific objectives of the present work were as follows:

1. Using the plasma device which produces an array of hypocycloidal pinches (HCP) perform a careful luminescence study to determine its capabilities and limitations as an optical pump.

2. Determine the critical parameters which govern the principal luminescence characteristics of the HCP.

3. Optimize the luminscence characteristics of the HCP.

4. Using the optimized HCP light perform lasing experiments on organic dyes of different lasing frequencies. Evaluate the overall performance of the HCP as an optical pump.

5. Look for an alternative plasma device with different pinch configuration which might work better than the HCP as an optical pump.

B. Status of Research

The highlights of the research achievements were as follows:

1. Detailed measurements were made on the luminescence characteristics of the HCP light, producing the following results:

   a. The light intensity variation when measured as a function of the capacitor bank storage energy resulted in a linear dependence. This was generally true at all wavelengths except that different intensities were registered at different wavelengths.

   b. The light intensity measured as a function of the fill gas pressure showed a peak. For example, the peak occurred at 4 torr for H_2 and O_2, and at 2 torr for H_2.

   c. The rise time of the light pulse increased with the fill gas pressure and decreased with the capacitor bank voltage. A qualitative explanation of this behavior was presented in the framework of the snow plow model.

   d. Low-level preionization of the fill gas was investigated in an attempt to shorten the rise time of the HCP light pulse. However, no detectable improvement resulted.

2. Extensive testing of the HCP device as an optical pump was done by using organic dyes as the lasing media. Laser activities were successfully achieved with all the dyes used (coumarin 480, LD 490, coumarin 504, and rhodamine 6G). A brief summary of the results is an follows:

   a. The output laser energy measured as a function of the capacitor bank voltage showed a superlinear behavior.

   b. The dependence of the output laser energy on the fill gas pressure showed a peak for each fill gas used. For example, the peak occurred at pressures between 3.5 to 4 torr for H_2 and D_2, and at 2 torr for N_2.

   c. The output power of the coumarin 480 laser was as high as that of the rhodamine 6G laser (which is considered to be unattainable with the commercial Xe flashlamps since their UV output is not as strong as their visible output), thus providing an experimental proof that the HCP light source is richer in UV than the commercial Xe flashlamps and that it is particularly suitable for pumping UV and blue-green lasers.

3. A Mather-type dense plasma focus (MDPF) device was identified as the alternative light source which has a plasma pinch configuration more efficiently implementable as an optical pump than HCP. A prototype MDPF device was designed and constructed for a preliminary experiment. Successful application of the MDPF light as an optical pump was achieved for the first time.

C. List of Professional Personnel Involved

Kyekyoon (Kevin) Kim, Principal Investigator, Professor.

Harry Rieger, Graduate Research Assistant, a Ph.D. candidate; currently with Acculase, San Diego, CA.

James J. Fanning, Graduate Research Assistant, a Ph.D. candidate; currently with Sandia Lab, Albuquerque, NM.

D. A Cumulative Chronological List Of Written Publications

1. H. Rieger and K. Kim, "Performance of an array of plasma pinches as a new optical pumping source for dye lasers," J. Appl. Phys., Vol 54, No. 11, pp. 6199-6212, November 1983.

2. J. J. Fanning and K. Kim, "A Mather-type dense plasma focus as a new optical pump for short-wavelength high-power lasers," J. Appl. Phys., Vol. 55, No. 7, pp. 2795-2796, April 1984.

C. Interactions (Coupling Activities)

1. J. J. Fanning and K. Kim, "Optical pumping of a dye laser with a Mather-type Dense Plasma Focus," paper presented at the 16th Workshop of the Industrial Affiliates Program in Physical Electronics, April 6-7, 1983, Urbana, Illinois.

2. K. Kim, H. Rieger, J. J. Fanning, "Dense plasma focus as a new pump light source for high-power lasers," paper presented at the Conference on Lasers and Electro-Optics, May 17-20, 1983, Baltimore, Maryland.

3. K. Kim and J. J. Fanning, "A new short-wavelength optical pump consisting of a Mather-type dense plasma focus," paper presented at the Conference on Lasers and Electro-Optics, June 19-22, 1984, Anaheim, CA.

II. EXPERIMENTAL DEVELOPMENT AND RESULTS

Using the hypocycloidal pinch (HCP) and the Mather-type Dense Plasma Focus (MDPF), lasing experiments were performed, respectively, to determine the capabilities as well as limitations of each plasma device as an optical pump for lasers. Detailed investigation was carried out with HCP, whereas the work performed on MDPF was limited to a preliminary feasibility assessment due to time and monetary constraints.

Since detailed written accounts of these studies have already been published as journal articles which are both comprehensive and self-contained, they are reproduced in the following to describe the work performed with HCP and MDPF, respectively.

A. Results from Hypocycloidal Pinch

Reproduced from:

Harry Rieger and Kyekyoon Kim

"Performance of an array of plasma pinches as a new optical pumping source for dye lasers"

J. of Appl. Phys., Vol. 54, No. 11, pp. 6199-6212, November 1983.

Performance of an array of plasma pinches as a new optical pumping source for dye lasers

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A new optical pumping source consisting of an array of plasma pinches in the hypocycloidal-pinch geometry is employed to pump a variety of dye lasers. A dye cuvette is inserted along the symmetry axis of the plasma device such that it may be surrounded by the plasma pinch. The light from the plasma pinch is very intense and rich in ultraviolet, which makes it an attractive optical pumping source for dye lasers, particularly in the blue-green spectral region. Control of the plasma fluorescence is achieved by the choice of gas, its fill pressure, and the capacitor bank voltage and its stored energy. The rise time of this "plasma flashlamp" depends mainly on the gas species and the fill pressure. Output energy of ~ 2 mJ per cm^3 of lasing medium, or 2 kW/cm^3 for a 1-μs laser pulse, is obtained from rhodamine 6G, coumarin 480, LD 490, and coumarin 504 dyes. That both the coumarin 480 and rhodamine 6G lasers have the comparable output power is a direct proof that the present optical pumping source is more efficient than the commercial xenon flashlamps in pumping lasers in the blue-green spectral region.

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I. INTRODUCTION

Although a variety of plasma compression devices has been designed to date to achieve mainly the conditions required for thermonuclear fusion, some have been found to have useful characteristics as a pumping source for lasers, particularly in the UV region of the spectrum.[1–8] These plasma compressors constitute a new family of optical pumping sources for the following reasons: first, they can handle high input energies; second, they produce an enhanced UV spectrum; and finally, they lend themselves to repetitive, simple, and long-lifetime operation.

Using a pinched discharge in an internal-tube configuration (coaxial flashlamp-type configuration), laser activities were previously obtained from rhodamine 6G with the output energies of up to 1 J/cm^3 and the maximum output power of 10 MW.[2,3] Excitation of organic dyes was also achieved using a plasma focus generated by a magnetoplasma compressor.[4,5] In that work, it was reported that the compressed plasma had the light efficiency of 25%–40%, η_{cl} of 0.7–0.9, the overall conversion efficiency as high as 0.24%, and the output power as high as 26 MW. Such a system could operate at a repetition frequency of 100 Hz. The hypocycloidal pinch (HCP), which was originally developed by Lee and co-workers,[1] is particularly suitable as an optical pumping source because one can form an array of such pinches to make it as long as desired. As shown in Fig. 1, the principal element of the HCP device is a set of three parallel disk electrodes, each having a circular hole at the center. The disk electrode in the middle is an anode common to the two outer electrodes, which are cathodes. The insulators placed between the electrodes are also in the form of a disk and provide an inverse pinch geometry for the initial breakdown currents. The lower and upper current sheets launched from the insulators advance radially, by the $\mathbf{J} \times \mathbf{B}$ force, toward the center hole where they collapse and interact with each other. As a result, a strong plasma is formed at the center of the apparatus. For detailed information on the HCP including the history behind its birth, the reader is referred to Ref. 1.

Plasma density of $\sim 10^{19}$ cm^{-3}, temperature of ~ 2 keV and lifetime of ~ 5 μs were achieved using the HCP device.[1] The use of this device as an optical pumping source, however, does not require such extreme parameters. The attractive features of the HCP device as an optical pumping source are: (1) it produces a hollow cylindrical column of pinched plasma, which allows insertion of a laser tube along the axis of the plasma cylinder for an efficient optical pumping. (2) Its metallic construction allows for the use of high input energies (higher than 30 kJ) and practically an infinite lifetime. (3) Its UV-enhanced plasma spectrum makes it a unique and powerful tool for optically pumping a variety of lasers. The bremsstrahlung spectrum of the plasma is much narrower than that of the Planckian distribution due to the plasma compression (approximately one fifth in width of the black-body radiation[4]). (4) Since the plasma stream is self-focusing, the achievable photon flux density at the active medium in the absorption band is believed to be an order of magnitude greater than other currently available gas discharge tubes. (By using a magnetoplasma compressor, which relies on a physical process similar to that of the HCP device, Kozlov and Protasov achieved a photon flux density of 2–3 $\times 10^{23}$ cm^{-2} s^{-1}.) (5) The physical length of the pump light can be extended as long as necessary by stacking up additional electrodes to form an array. (6) By properly controlling the external parameters, such as the fill gas pressure, gas species and capacitor bank voltage, the HCP apparatus can be tuned to produce short-to-long light pulses, slow-to-fast rise times, and visible-to-UV fluorescence spectra. Therefore, under the

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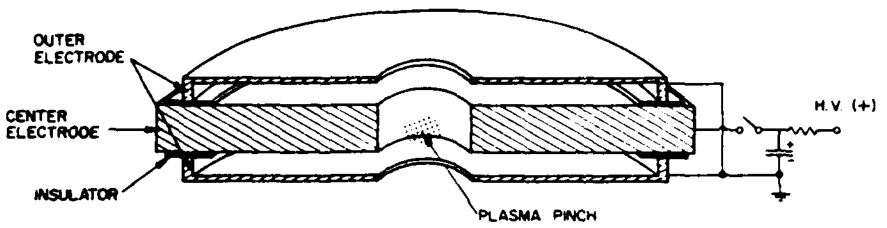

FIG. 1. Schematic of hypocycloidal-pinch plasma device.

appropriate conditions, the HCP device can produce pump light pulses suitable for pumping a wide variety of laser materials.

Some time ago, using such a device, Lee and his coworkers produced iodine, xenon recombination, and atomic fluorine lasers.[6,7] By improving the design and performance of a similar device, we have recently succeeded in pumping a dye laser for the first time. (A brief account of this preliminary work is reported in Ref. 8.) Since then, an extensive investigation has been carried out to thoroughly evaluate the performance of the HCP plasma as a new optical pumping source for dye lasers. A detailed account of this performance evaluation is included in the present report. A brief description of the requirements for and advantages in pumping dyes with the HCP array is first presented in Sec. II. Details of the HCP plasma flashlamp system designed to pump a variety of dye lasers are then described in Sec. III. Experimental results are presented and discussed in Sec. IV, which include the characterization of the HCP plasma light, the pumping of dye lasers, the effects of various physical parameters affecting the overall system performance, and some general remarks on the HCP plasma-dye laser system. Section V is for the conclusion.

II. REQUIREMENTS FOR AND ADVANTAGES IN PUMPING DYES WITH HCP ARRAY

Organic dyes exhibit a short fluorescence lifetime of the upper singlet state S_1 (~ 10 ns). In addition, the singlet state S_1 can make a nonradiative transition to the triplet state T_1. Since this triplet state has a very long lifetime (~ 1 μs), it can deplete the population of the ground state S_0. This phenomenon, commonly known as the "triplet quenching," puts the limit on how fast the pumping rate to the upper singlet state should be to achieve laser activities.

The requirements for pumping dye lasers are: (1) The pumping rate of the excitation light source should exceed the threshold value before the triplet quenching becomes significant. (2) The spectra of the pumping source should overlap the absorption spectra of the dye. For example, an enhanced UV pumping spectrum is needed for efficient pumping of blue-green dyes and also when high concentration of dye is used.

The capability of the present plasma device to produce intense UV pump pulses makes it a promising source for high power dye lasers. An investigation of the plasma light pulse and spectrum was first carried out to specifically meet the requirements for lasing organic dye solution.[9,10] A dye cuvette was then inserted into the plasma chamber for lasing studies, which resulted in laser output energies of ~ 10 mJ (~ 2 mJ per cm^3 of lasing volume) from rhodamine 6G, LD 490, coumarin 480, and coumarin 504 dyes.

III. PLASMA-PINCH FLASHLAMP SYSTEM FOR PUMPING DYE LASERS

By operating the HCP plasma device in the hollow cylinder mode (namely, by forming the plasma pinch in a hollow cylindrical shape), one may insert a laser tube along the axis of the plasma column. It is desirable to uniformly illuminate the laser tube. And, in particular, to achieve high laser gain and power, the laser tube should be relatively long. This, in turn, requires a long plasma column. When the need arises, additional electrodes may then be added to form an array of plasma pinches as shown in Fig. 2.

Figure 2 is a cross-sectional view of a two-stage plasma device with a laser tube inserted along the axis. The disk electrodes were fabricated out of aluminum for light weight, low cost, and high conductivity. High quality 1/8-in.-thick fiberglass rings were used to isolate the electrodes. To prevent their contamination during the discharge, these fiberglass rings were covered with pyrex rings. *O*-rings were used to seal the electrode assembly and to insure a vacuum tight chamber. Threaded rods were inserted along the edges of the ground disks to hold the entire structure in a stable position. The coaxial cables were connected to the disk electrodes in a

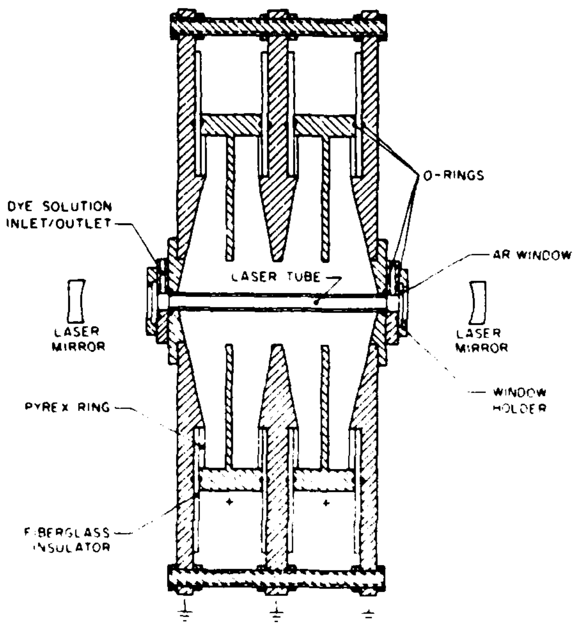

FIG. 2. HCP plasma device used to pump dye laser.

symmetric manner: all cables were of the same length and connected symmetrically around each disk. The resulting structure of this double-stage array was such that it remained intact through numerous high-energy shots. After firing it over 10 000 times, the device was carefully inspected, but no damage could be found. To minimize losses within the laser cavity, the flat AR windows were positioned directly at the end of the plasma device. In this way, the entire lasing volume could be pumped by the plasma-pinch flashlamp. Maximum utilization of the light incident on the laser tube was achieved by choosing the i.d. and o.d. of the laser tube at the ratio of 1.5, the index of refraction of the laser tube.

Efficient excitation of dye lasers requires a short rise time of the plasma flashlamp and an adequate match between the emission spectrum of the plasma and the absorption spectrum of the dye. There are several parameters that play a role in determining the emission characteristics of the plasma light: (1) the gas species used, (2) its fill pressure, (3) the input energy and voltage, and (4) the system inductance.

The necessity to vary the gas species and the pressure required the HCP array to be housed in a vacuum tight chamber. The chamber was then evacuated to a low pressure and filled with a variety of gases at a desired pressure. Also, to handle high input energy (~ 20 kJ) and voltage (~ 20 kV) a large capacitor bank was required. A high-voltage power supply was used to charge the capacitor bank. To transfer the stored energy from this capacitor bank to the HCP array, a home-made high-coulomb gap switch was used.

Figure 3 shows a schematic diagram of the overall electrical system. The power supply has the output voltage up to 30 kV and the load current up to 50 mA. Resistance R represents the limiting resistor that prevents overloading the power supply when the capacitor bank is fully discharged. The high voltage relay is needed to control the voltage and/or energy of the capacitor bank. The charging control system is set to the desired voltage, and automatically opens up the high voltage relay when the capacitor bank reaches that value. The capacitor bank consists of 6 capacitors, each rated at 20 kV, with their parallel combination producing a total capacitance of $\sim 85\ \mu$F. The high-coulomb gap switch is for a a fast discharge of high energy. The trigger remote control is similar to a conventional car ignition system and produces a spark to initiate the discharge when desired. The discharge energy is in turn distributed evenly through 40 coaxial cables to the periphery of the HCP disk-electrodes for symmetric discharge.

To achieve the shortest possible light-pulse rise time, one must have the lowest possible inductance for the discharge circuit. The six capacitors of the capacitor bank are connected in parallel using a 9-in.-wide aluminum strip on the positive side and a 11-in.-wide aluminum strip on the ground side. In addition, the aluminum strips are isolated with a thin mylar sheet. This sandwich configuration produces a transmission line with a low inductance and high capacitance, resulting in a low characteristic impedance ($Z = L/c$).

Multichanneling of rail-gap switches would result in the lowest possible inductance. However, due to its simplicity and operational practicality, the gap switch shown in Fig. 4 was chosen for the present study. The gap switch electrodes shown in Fig. 4 are 7.62 cm in diameter and are designed to provide a wide arc-discharge region and low inductance. The electrodes are spaced such that they can hold 20 kV in air with no breakdown. The bottom electrode is tied directly to the positive plate of the capacitor bank, and the top electrode is connected to a copper plate that holds all the center conductors of the 40 coaxial cables leading to the HCP device. The metal housing of the switch is used as the ground path for the coaxial cables, and also dampens the discharge sonic shock wave. The spark plug, located at the center of the bottom electrode, is employed to trigger the switch.

A steady flushing of the gap switch with nitrogen or dry air is necessary for a clean operation under high energies. The high energy operation of the gap switch also requires the use of a teflon insulator that can sustain high temperatures and sonic shock waves and the use of a tungsten rod for the spark plug. To reduce erosion, the surface layer of the electrodes is fabricated out of elkonite instead of plain copper. During the present investigation, the electrodes lasted several thousand shots, but the teflon insulator had to be replaced every two to three hundred shots.

To maintain better homogeneity and to reduce thermal instabilities in the active volume of the lasing medium, the

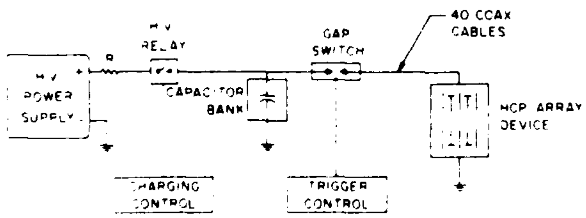

FIG. 3. Schematic diagram of the electrical system for the HCP array device.

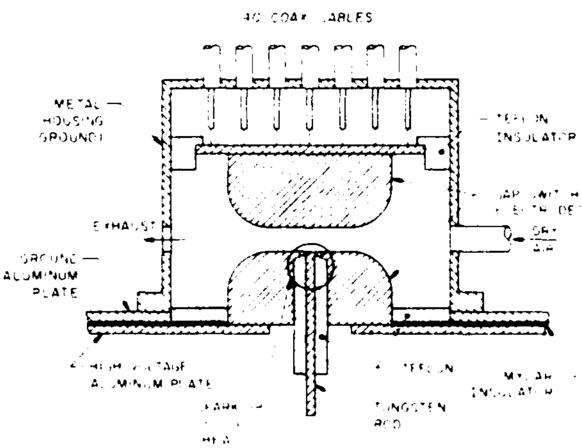

FIG. 4. Spark gap switch.

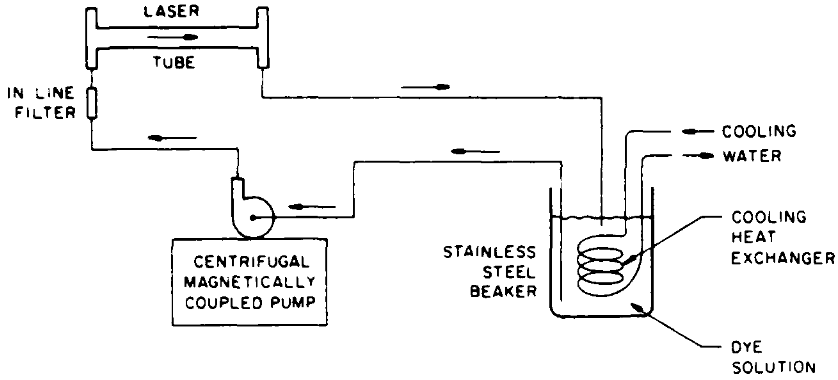

FIG. 5. Schematic diagram of the dye solution flow system.

dye solution needs to be circulated for the pumping of dye lasers. The circulation and cooling of the dye solution were done, respectively, using a micropump with a magnetic-coupled centrifugal head and by flowing the dye through a stainless steel, water-cooled heat exchanger bath as shown in Fig. 5. Teflon tubes were used to connect the fluid pump and beaker to the adapting heads of the plasma chamber designed to hold the laser tube. The adapting heads were made out of stainless steel and sealed with silicon rubber *O*-rings. To reduce the bubbles in the dye solution, a 0.5-μm Nupro in-line filter was installed in the dye transfer tube.

IV. EXPERIMENTAL RESULT AND DISCUSSIONS

A. Characterization of HCP plasma light

The fluorescent characteristics of the plasma device were first studied to determine the adequacy of the plasma light as a potential optical pumping source for lasers. Measurement of the light output versus the capacitor bank energy produced a linear dependence as shown in Fig. 6. By using a Heath Monochromator and photomultiplier assembly, the same linear dependence, although of different intensities, was observed at different wavelengths.

Another parameter studied was the plasma light pulse rise time, which is an important parameter to be controlled for the pumping of dye lasers. Figs. 7 and 8, respectively, show the dependence of the plasma light pulse rise time on the capacitor bank voltage and on the fill gas pressure for the case of hydrogen. Since the ionization avalanche process is accelerated at high voltages, the plasma light pulse rise time is expected to get shorter at higher voltages. Also, the propagation velocity V_p of a thin plasma sheet, according to the "snow plow" model,[11] is a function of the capacitor bank voltage E and is given by $V_p \propto E^{1/2}$. Since the characteristic propagation time t_p of the plasma sheet should be inversely proportonal to V_p, $t_p \propto E^{-1/2}$. It is, therefore, natural to expect that the plasma light pulse rise time should decrease quickly as the capacitor bank voltage is increased. This general behavior is clearly shown by Fig. 7.

The dependence of the rise time on the fill gas pressure is shown in Fig. 8. To fully understand this rise-time behavior, the following investigation was carried out. First, the emission spectrum was measured using a spectrograph. This resulted in two distinctly different spectral distributions, one for pressures below 1.5 Torr and the other for pressures above 1.5 Torr. Two such spectra are shown in Fig. 9 for He gas. The spectrum above 1.5 Torr is clearly that of He, while the one below 1.5 Torr is interpreted to be that of the impurities and He gas. With these observations, it is, therefore, not surprising to see in Fig. 8 that the effect of the impurities gradually diminishes as the fill gas pressure is increased and that the plasma fluorescent dynamics follow that of the usual plasma pinch formation of the fill gas at and above 1.5 Torr.

According to the "snow plow" model,[11] the plasma sheet velocity V_p is also a function of the fill gas pressure P, given by $V_p \propto P^{-1/4}$. Therefore, $t_p \propto P^{1/4}$. One should expect to see an increase in the plasma light rise time with

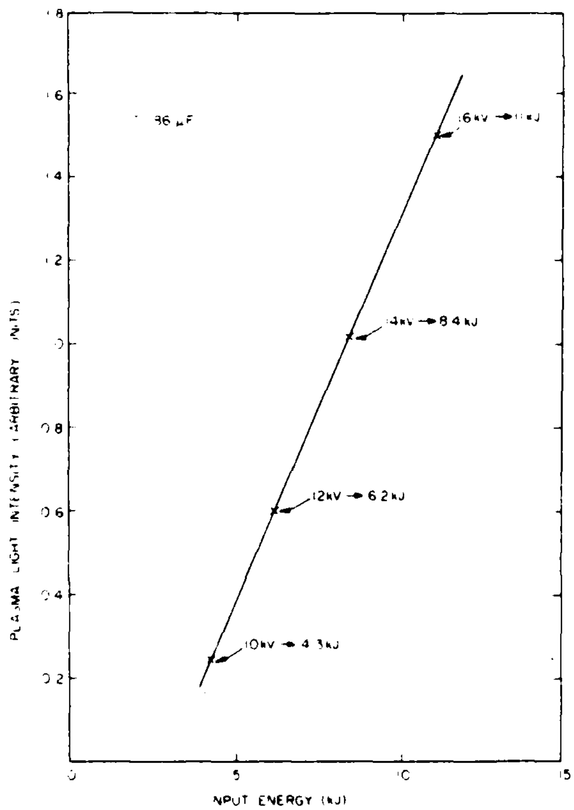

FIG. 6. Input capacitor bank energy vs output plasma light intensity.

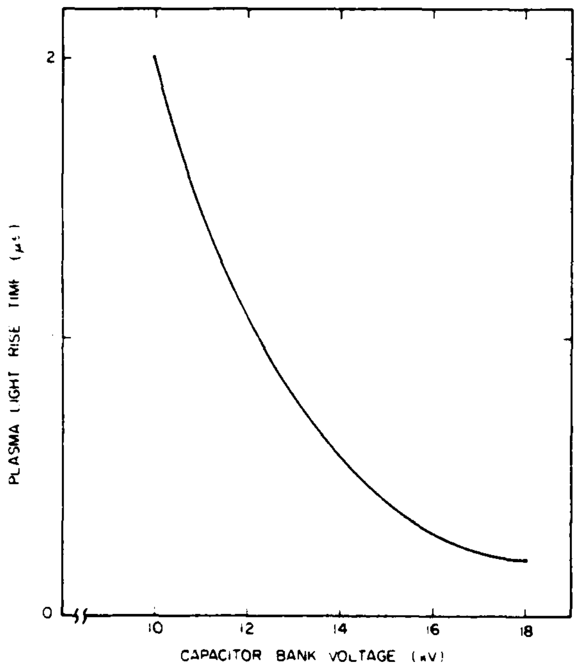

FIG. 7. Plasma radial light rise time vs capacitor bank voltage at 2 Torr of H_2.

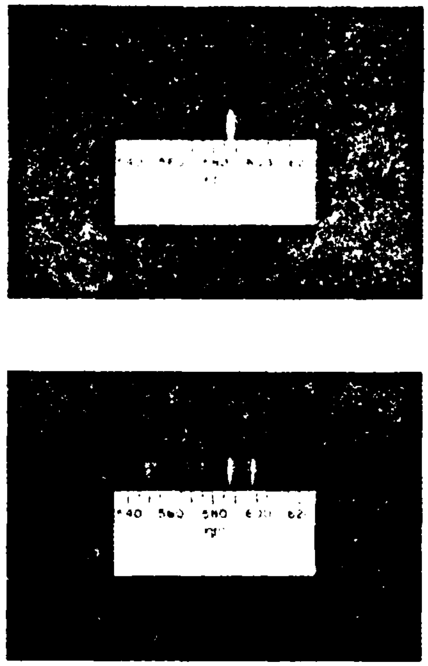

FIG. 9. (a) Plasma light spectrum of He gas at fill pressure of 5 Torr; (b) added spectrum of impurities and He gas at 0.5 Torr of He.

increasing pressure, which is seen in Fig. 8 at and above 1.5 Torr.

The performance of the system should, in general, improve as the capacitor bank voltage is raised, since the linear increase in the pump light intensity (Fig. 6), in addition to shorter rise time (Fig. 7), should allow for more efficient pumping of dye lasers at higher voltages. Of the wide variety of gases tested, H_2, D_2, N_2, and air turned out to be the most suitable in producing the desired rise time, intensity, and spectrum of the plasma light. As shown in Fig. 10, the plasma light energy flux density was measured for different fill gas pressures by inserting a joulemeter inside the quartz tube installed along the device axis. Figure 11 shows the light intensity dependence on the gas fill pressure for D_2 (solid line) and N_2 (dotted line) gases. The results for H_2 and air were, respectively, similar to that of D_2 and N_2. The features common to all the gases tested are as follows: Until the plasma chamber pressure reaches certain values (2 Torr for N_2 and 5 Torr for D_2), the plasma light energy flux continues to increase due to the growing proportion of the ionized gas. Further increase in pressure beyond those values, however, causes the light energy flux to decrease since the increased

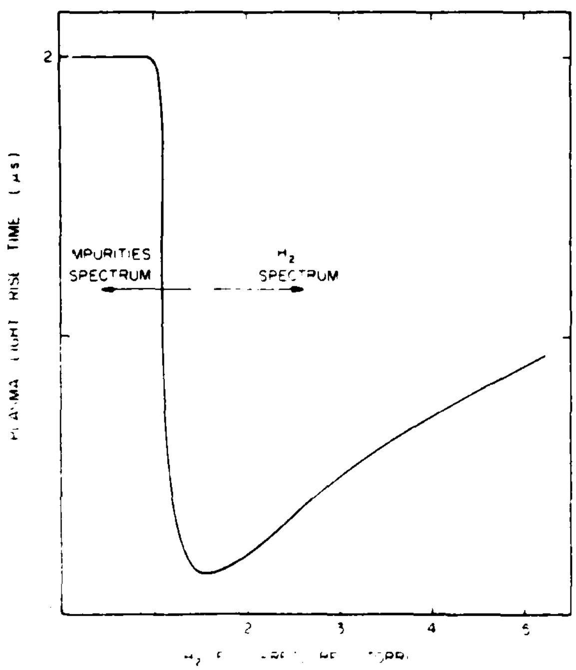

FIG. 8. Plasma radial light rise time vs H_2 fill pressure at 18 kV.

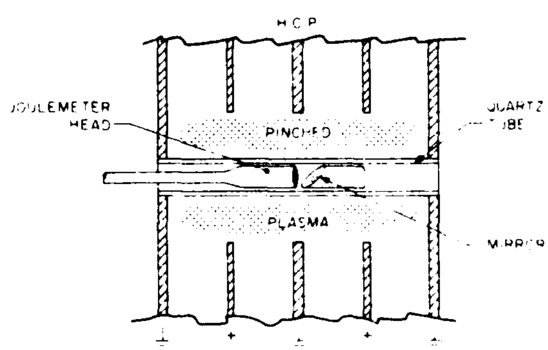

FIG. 10. Schematic of the setup used for measuring plasma light energy distribution along the HCP device axis.

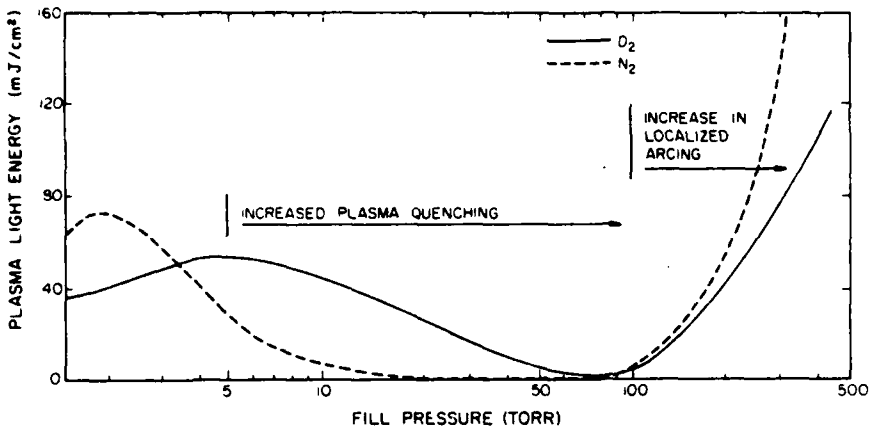

FIG. 11. Plasma light energy vs fill pressure of D_2 and N_2 at 16 kV.

collisions among the plasma particles result in nonradiative energy loss. This light quenching process persists until the pressure reaches the value of ~100 Torr. As the pressure is further increased, a different plasma dynamics takes place: any electrode nonuniformity will allow a lower impedance path for the discharge current. The high density (or pressure) of particles then allows further ionization along the path, giving rise to an avalanche of localized arcing. The higher the pressure, the narrower and brighter the arc discharge paths. Evidence of such a phenomenon could be seen, as the erosion marks were detected on the electrode surface. A few random spots indicating localized high-current discharge were also found. No erosion spots on the electrode surface were, however, observed when a low pressure in the nonarcing pressure regime was used.

The emission spectrum of the plasma pinch also depends on the fill gas pressure. There are two competing factors: one is the line spectrum of the specific gas species used and the other is the continuum bremsstrahlung radiation. The line emission increases with a decrease in the fill pressure due to the decreased collision-induced photon quenching. The continuum emission becomes dominant at higher pressures due to more frequent collisions of the plasma particles. In addition, the continuum spectrum shifts with a change in the fill pressure. A lower pressure leads to a shorter wavelength distribution of the continuum spectrum because the same amount of the total energy is now distributed among fewer particles. As a result, a higher per-particle energy is obtained.

From the behavior of the light-pulse rise time and intensity versus the pressure, one can see that a desirable pumping light pulse for dye lasers may be obtained at the maximum input energy by using ~3–5 Torr of H_2 or ~2 Torr of N_2. At low pressures and high input energies, the pump light pulse spectrum is rich in UV. This means that, if a hypocycloidal pinch plasma is to be employed as an optical pumping source for dye lasers, use of a UV filter might be necessary to minimize photodissociation of a certain class of dyes.

B. Pumping of dye lasers using plasma pinch flashlamp

Having done the preparatory characterization of the plasma fluorescence for an application to the optical pumping, especially of dye lasers, the next step was to build a dye laser system. The first dye laser tube was designed with the intention of eliminating all the possible factors that might interfere with the laser action. The inside diameter of the laser tube was chosen to be only 3 mm since it is easier to achieve uniform excitation of the lasing medium of a small cross-sectional area. A dye with absorption cross section $\sigma(\lambda)$ (cm^2) and density ρ(cm^{-3}) would have an absorption length $L(\lambda)$ of $L(\lambda) = [\sigma(\lambda)\rho]^{-1}$ for the wavelength. Hence, the smaller the radius of the laser tube, the easier it is to meet the condition of $R < L_{eff}$, where R is the inner radius of the laser tube and L_{eff} is the effective absorption length for the pump light in the absorption spectrum of the dye.

Rhodamine 6G was selected for the first attempt because of its demonstrated highest power output amongst a variety of dyes pumped with a flashlamp. The dye concentration was chosen to be 1.2×10^{-4} M/ℓ to ensure a high enough gain without causing the concentration quenching. UV filtering was done by surrounding the laser tube with a larger diameter glass tube and by filling the volume in between the two tubes with benzyl benzoate.[12]

To reduce intracavity losses: (a) The end pieces of the HCP device, which hold the laser tube, were constructed such that the amount of dye within the cavity, that is not exposed to the pumping light, could be minimized; (b) Antireflection windows were used to reduce the glass-to-air interfacial loss; and (c) Maximum reflection dielectric mirrors were used to form a stable cavity.

The plasma chamber was first pumped down to 10^{-4} Torr, and then filled with D_2 to a pressure of ~4 Torr. A steady flow of dye solution cooled by tap water was maintained to reduce the possible nonuniformities in the index of refraction throughout the lasing medium. The capacitor bank was then charged to 16 kV, and when switched to the plasma system, a laser pulse such as shown in Fig. 12 was detected using a fast photodiode.

The time delay between the pump light and the laser pulse is attributed to the threshold pump rate condition that had to be met before the laser action could be achieved. The termination of the laser pulse took place within 1 μs, regardless of the pumping pulse intensity or width. At the beginning, thermal instabilities in the dye laser solution were sus-

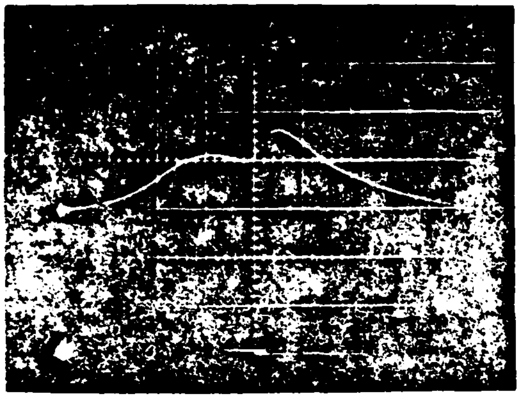

FIG. 12. Simultaneous oscillograms of the excitation light pulse from the plasma pinch (top), and the resulting dye laser pulse (bottom) using 3.75 Torr of H_2 fill gas at 16 kV.

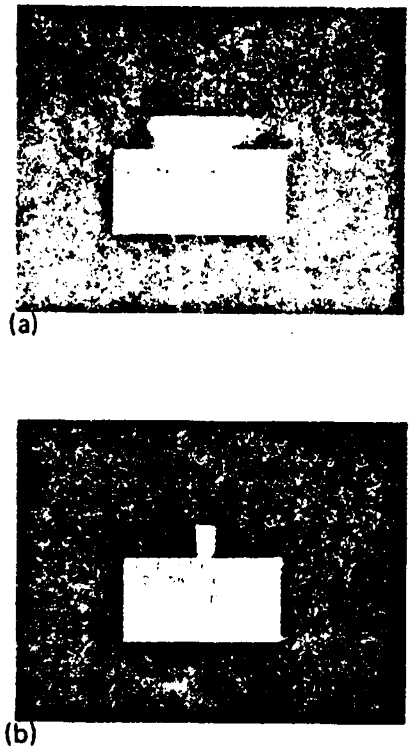

FIG. 13. (a) Spontaneous emission spectrum from rhodamine 6G dye, and (b) the stimulated spectrum of the dye laser.

pected to be the cause for an early termination of the laser pulse. However, further experiments confirmed that the triplet-state quenching is the cause for an early termination. Chemical additives, such as cyclo-octatetraene and cycloheptatriene, have been known to reduce the triplet quenching, thus producing longer laser pulses.[13] However, no attempt was made to use these additives in the present study.

Spectrum narrowing, which is an indication of the laser action, was verified using a spectrograph as shown in Fig. 13. The spontaneous emission spectrum shown in Fig. 13(a) corresponds to that of rhodamine 6G. A substantially narrower spectrum was obtained when the output spectrum was dominated by the stimulated emission as shown in Fig. 13(b). The relatively wide output spectrum (> 50 Å) is typical for dye lasers, which makes the dye lasers very attractive as tunable lasers.

The laser system and the diagnostics used in the experiment are schematically illustrated in Fig. 14. The diagnostics setup was designed to simultaneously monitor all the important parameters required to evaluate the laser system performance. Quartz windows on the outer electrodes, next to the laser tube, allowed for the monitoring of the plasma-light-pulse shape and spectrum. The plasma light pulse was detected by the fast photodiode PD 1 (Motorola MRD 510), which has a response time of ~ 1 ns when terminated at the oscilloscope input with a 50 Ω resistor. The rise times of all the oscilloscopes used were less than 20 ns, much faster than the events under investigation. The light spectrum was obtained by a Jarrell-Ash Mark-X spectrometer, which had been modified to accommodate a Polaroid back film holder. The laser output signal was measured with a wide area photodiode PD 2 manufactured by Silicon Detector Corporation (SD-444-11-21-17). The response time of this diode was ~ 11 ns when terminated at the oscilloscope input with a 50

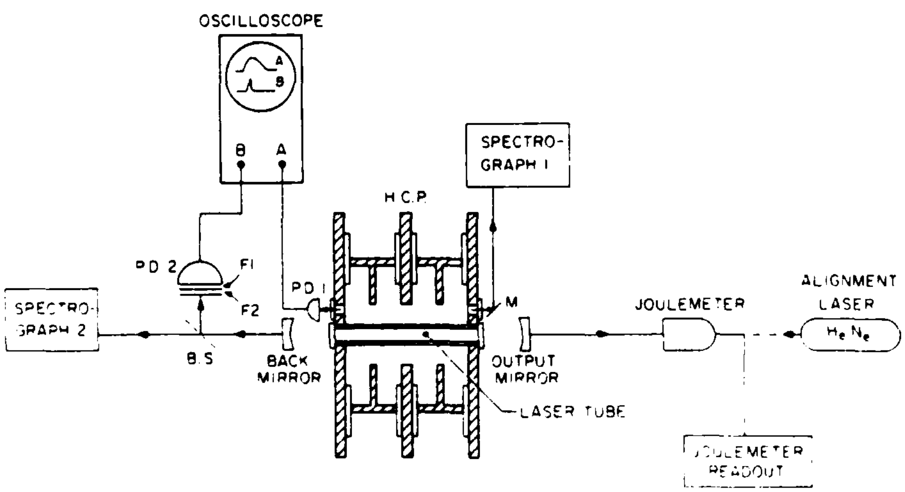

FIG. 14. Schematic of the experimental setup of the HCP array dye laser system.

Ω resistor. The active surface area of the diode was 1 cm^2. A 100-Å passband filter was placed in front of the photodiode to selectively detect the laser output only. Neutral density filters were also used to cut down the incident light intensity on the photodiode and to maintain the detection within the linear region of the photodiode response.

The signals from the two photodiodes were displayed simultaneously on a dual beam oscilloscope (Tektronix 551) and recorded on a Polaroid film. The output energy of the laser was measured by a joulemeter (Gen-Tec Model ED-200), and displayed digitally on a digital joulemeter readout (Gen-Tec Model PRJ-D). The active surface area of the joulemeter was 4 cm^2, which was large enough to capture the entire laser beam.

The potential of the present plasma pinch system as an optical pumping source for dye lasers can be evaluated by studying the effects of those parameters which may affect the overall laser system performance: (a) UV filtering, (b) capacitor bank voltage, (c) plasma gas species, (d) fill gas pressure, (e) preionization, (f) dye solution composition, (g) output laser mirror reflectivity, and (h) dye concentration. A brief account of the investigations that were carried out to study the effects of these parameters is next presented.

1. UV filtering of HCP plasma light spectrum

The present "plasma flashlamp" system is superior to other flashlamps in that its fluorescent spectrum is richer in UV. In the first experiment that led to dye laser activities, a large portion of the UV spectrum was filtered out as a precautionary measure to minimize the UV-induced photo-dissociation of the dye. Utilization of UV is desirable when a high-density lasing medium and a large laser tube diameter are used. Due to the small UV-absorption cross section of the dye, the UV light can penetrate the dye deeply. A UV-enhanced spectrum is also advantageous for efficiently pumping short-wavelength dye lasers in the blue and blue-green spectral region.

A single quartz laser tube (7 mm i.d. and 10 mm o.d. for maximum light coupling) replaced the previous dual-tube design in which two coaxial tubes were used with the outer tube filled with benzyl benzoate for UV filtering. Note that the cutoff spectrum of quartz is ~180 nm. When the system was fired at intervals of ~1 min using rhodamine 6G dye, reduction in the output power was noticeable due to the degradation of the dye. Namely, the UV photodissociation of the dye reduces the effective dye concentration available for laser action. In addition, the dissociated dye increases the cavity losses by increasing absorption at the laser oscillation frequency. The photodissociation of the dye is reversible to some degree. When the system was fired at intervals of ~10 min, a smaller reduction in the laser output power was detected. When fired at intervals of 24 h, the system showed almost no reduction in the laser output power.

On the contrary, when coumarin dyes such as coumarin 480 were used, no reduction in the output laser energy was observed. The explanation for this is that coumarin dyes have strong absorption in the near-UV spectral region and, as a result, the output laser energy increases when a quartz tube is used instead of pyrex.

To minimize the UV photodissociation of rhodamine 6G dye, the quartz tube was replaced by a pyrex tube of the same dimensions. The spectral cutoff of pyrex is ~350 nm, and therefore, it is natural to see the reduction in the UV photodissociation of the dye with the pyrex tube in use. Only a slight reduction in the output laser energy could be observed when the system was continuously fired at intervals of 1 min for 100 shots. Since most of the experiments described in this work were conducted with rhodamine 6G, it is to be assumed, unless otherwise specified, that a pyrex tube of 7 mm i.d. and 10 mm o.d. was used for the study.

2. Effect of gas species and pressure on plasma light pulse characteristics

The dynamical behavior of the plasma pinch depends on several parameters: (1) The electrode configuration of the plasma device, (2) the electrical circuit (capacitor bank size and voltage, switch, and effective resistance and inductance of the system), and (3) the gas species and pressure.

Different gases possess different work functions. As a result, the dynamics of the ionization avalanche is different for each gas which, in turn, affects the rise time, intensity, and duration of the plasma light pulse. In addition, the mass of the individual gas particles is a factor in determining the propagation velocity of the plasma sheet which, in essence, shapes the rise time and duration of the plasma light pulse. The effect on the plasma dynamics of the increasing gas pressure is that it decreases the per-particle-energy of the propagating plasma ions, thus slowing down the plasma sheet. Longer rise times and durations are, therefore, expected of the light pulse at higher gas pressures. These general observations are clearly exhibited by Fig. 15 in which four oscillograms of the plasma fluorescence are shown for different gas species and pressures.

The emission spectrum of the plasma is composed of the line spectrum of the specific fill gas plus the usual continuum bremsstrahlung spectrum of the ionized gas particles. The continuum spectrum is a strong function of the fill gas pressure since the number of particles among which the input energy is distributed depends on the fill gas pressure which, in turn, determines the temperature of the plasma. Different continuum spectra corresponding to the plasma temperatures are, therefore, expected at the different gas fill pressures.

Laser action was obtained when H_2, D_2, N_2 and air were used as the fill gas. Although a few Torr of Xe gas produced higher-energy light pulses than that of the other gases tested, no laser action could be obtained with Xe due to the slow rise time of the light pulse (~30 μsec). Figure 16 shows two laser traces of rhodamine 6G dye obtained, respectively, with H_2 and N_2. The delayed lasing observed in the case of N_2 pumping is due to the slower pumping rate.

Measurements of the output laser energy versus the fill gas pressure for H_2, D_2, and N_2 (Fig. 17) show slightly different dependences on the fill gas pressure. As shown by Fig. 11, H_2- and D_2-plasma light intensities peak at the pressure of 5 Torr. However, the pumping light pulse rise time, as shown by Fig. 8, shortens as the pressure is lowered. The result is an optimum condition which occurs at the fill pres-

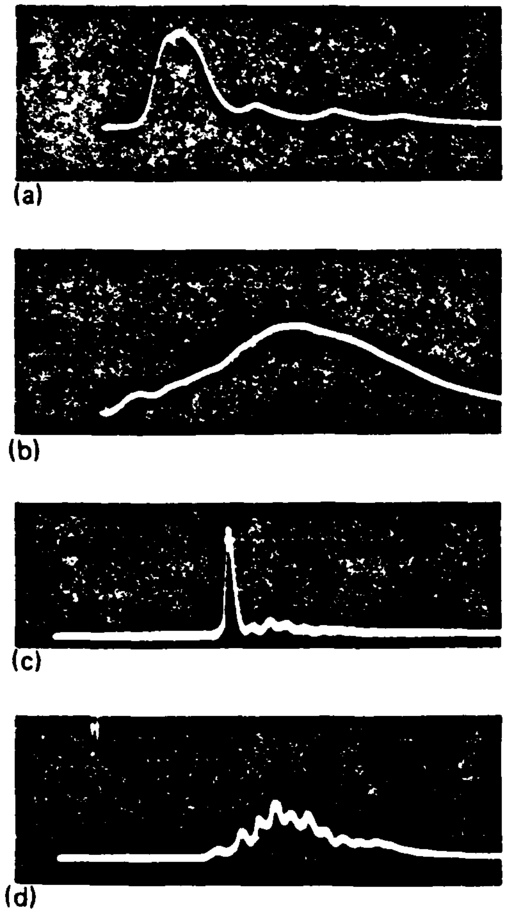

FIG. 15. Plasma light pulses for different gas species and pressures. The vertical and horizontal axes, respectively, represent the light intensities in arbitrary units and the time scales specified in the parenthesis for each case. (a) 1.5 Torr of He (5 μs/div), (b) 1.5 Torr of Xe (10 μs/div), (c) 5 Torr of D (20 μs/div), and (d) 400 Torr of D (20 μs/div).

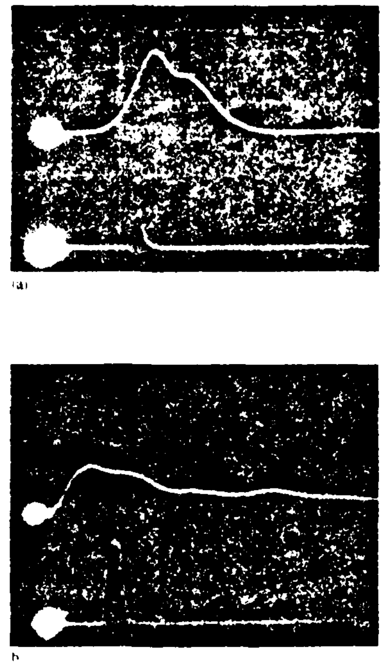

FIG. 16. Simultaneous oscillograms of the excitation light pulse (top) and the dye laser pulse (bottom). The vertical and horizontal axes, respectively, represent the light intensities in arbitrary units and the time scales of 2 μs/div. (a) Using 3.75 Torr of H_2 fill gas at 16 kV. (b) Using 2 Torr of N_2 at 16 kV.

sures between 3.5 to 4 Torr for both H_2 and D_2. The differences in H_2 and D_2 are probably due to the differences in mass because, as noted before in conjunction with Fig. 11, both D_2 and H_2 show similar light intensity dependences on the gas fill pressure. The N_2-plasma light intensity, as shown by Fig. 11, peaks at the fill pressure of 2 Torr. At this pres-

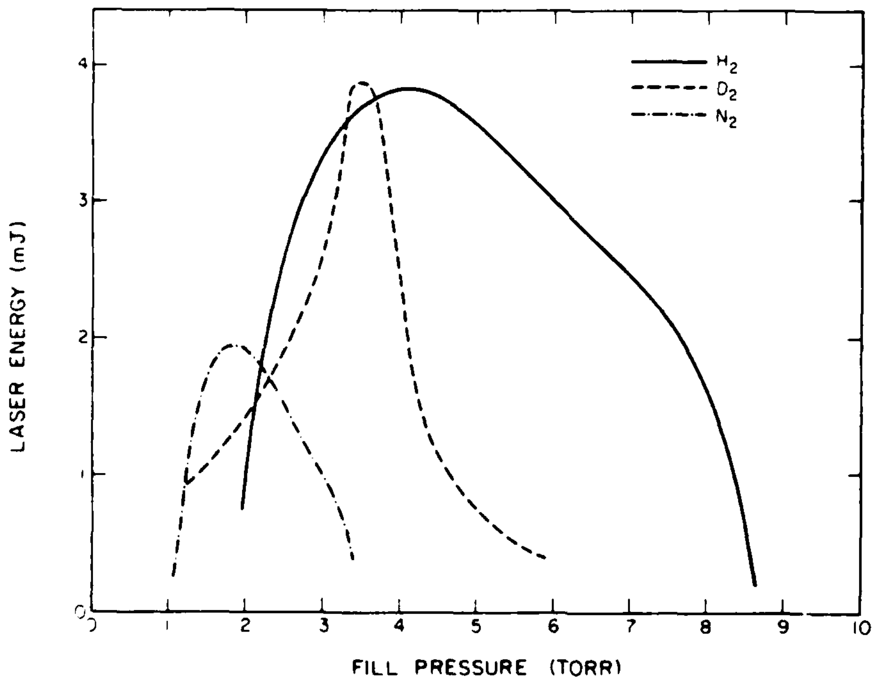

FIG. 17. Laser output energy vs fill pressure of H_2, D_2, and N_2 using 2×10^{-4} M/l of rhodamine 6G dye solution, 17 kV, and 95% output mirror reflectivity.

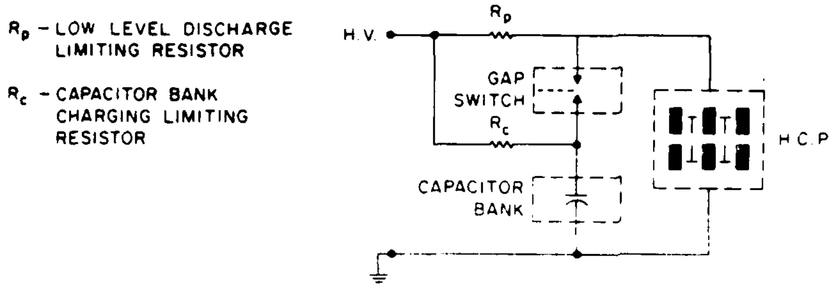

FIG. 18. Electrical diagram of the low-level discharge circuit for preionizing the HCP fill gas.

sure, the plasma light pulse rise time is also at its minimum. Therefore, the laser energy peaks at the pressure of 2 Torr for the N_2 pumping.

3. Effect of preionization

Improvement of the plasma light pulse characteristics, especially the shortening of rise time, is desired for efficient pumping of dye lasers because it leads to minimization of the triplet quenching. The ionization avalanche process is a key factor in determining the pulse light rise time. Preionization may accelerate the ionization avalanche process and, thereby, shorten the pumping light pulse rise time. There are several techniques for achieving preionization: (1) electron beam injection, (2) microwave heating, (3) UV photodissociation, and (4) low-level discharge. However, due to the required uniformity of the preionization and the particular configuration of the present plasma device, the low-level discharge can be most easily adopted.

A steady low-level discharge was maintained between the HCP electrodes using the setup illustrated in Fig. 18. In this setup, the same high voltage power supply that charges the capacitor bank provides a low discharge current through the resistor R_p. Measurements of the plasma light pulse, however, showed no detectable improvement in the light pulse rise time. In other words, the low-level preionization of the fill gas did not show noticeable improvement in the acceleration process of the ionization avalanche. On the other hand, the laser light pulse showed a slight decrease in its output energy. It is possible that the emitted light from the low preionization discharge allows for low-level buildup in the triplet state of lasing medium such that the same plasma-light pumping pulse may not produce a laser beam of the same energy that would have been possible in the absence of preionization.

4. Effect of capacitor bank voltage on laser output

As shown in Fig. 19, measurements of the output laser power and energy as a function of the capacitor bank voltage showed a superlinear response at the fill pressure of 4 Torr of H_2 regardless of the dye concentration. This superlinear response is not a total surprise due to the following reasons. First, one notes that achieving the threshold pumping rate for laser action depends on the pump light pulse intensity and rise time. In the present work, the light pulse intensity is linear with the input energy (Fig. 6), but, in addition, improvement in the pumping pulse rise time is obtained at higher voltages (Fig. 7). The combined improvement in the fluorescent intensity and rise time, therefore, further improves the pumping efficiency. The plasma pinch dynamics at higher voltages also enhances the already improved pumping efficiency: the higher the capacitor bank voltage, the closer the plasma pinch to the laser tube, which allows for utilization of a larger portion of the pumping light. By having the light source a distance r from the laser tube, instead of a great distance R, the coupling efficiency would be improved by a factor of R/r. The net effect of the improved plasma light pulse characteristics at higher capacitor bank voltage is, therefore, an enhanced pumping efficiency with a superlinear dependence.

The fluorescent behavior of organic dyes enhances the superlinearity even further. The singlet state lifetime is of the order of ~ 1 ns. On the other hand, the singlet-triplet intersystem crossing is slow (~ 10 ns). The triplet state lifetime is the slowest (~ 1 μs). Therefore, the population buildups of the singlet and triplet states are not proportional to each other. When a fast pumping rate is imposed on the system, threshold condition for the laser action is achieved earlier. This results in decreased intersystem crossing from the singlet to the triplet states and, hence, small intercavity losses

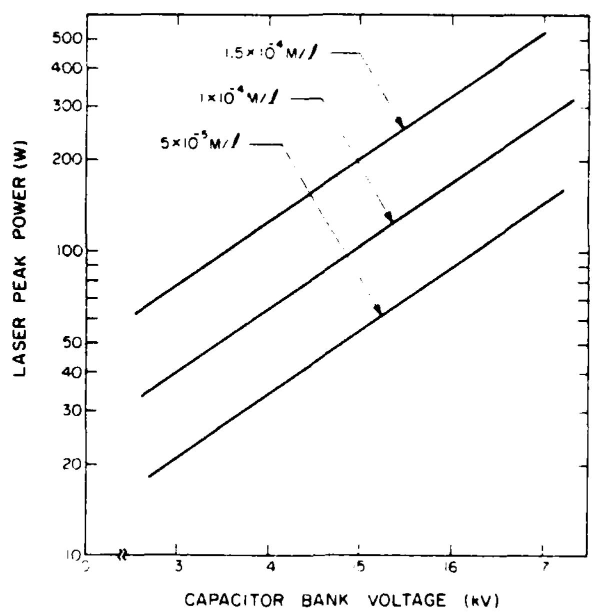

FIG. 19. Output dye laser peak power vs capacitor bank voltage for different dye concentrations, using rhodamine 6G dye, 3.75 Torr of H_2 fill gas, and ~99.8% output mirror reflectivity.

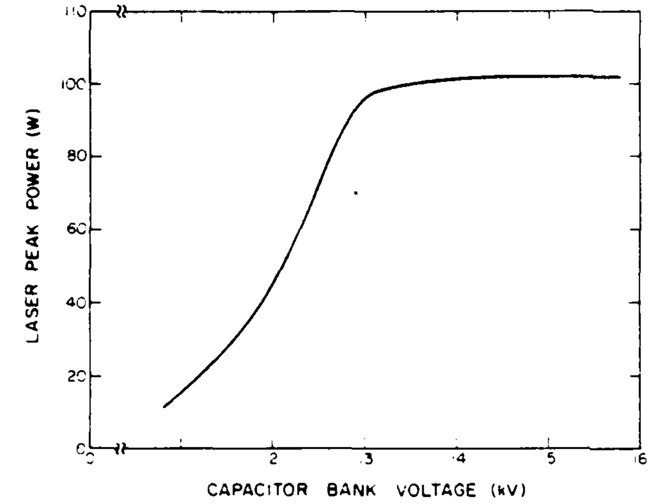

FIG. 20. Output dye laser peak power vs capacitor bank voltage, using 2 Torr of N_2, 1.2×10^{-4} M/ℓ rhodamine 6G dye, and ~99.8% output mirror reflectivity.

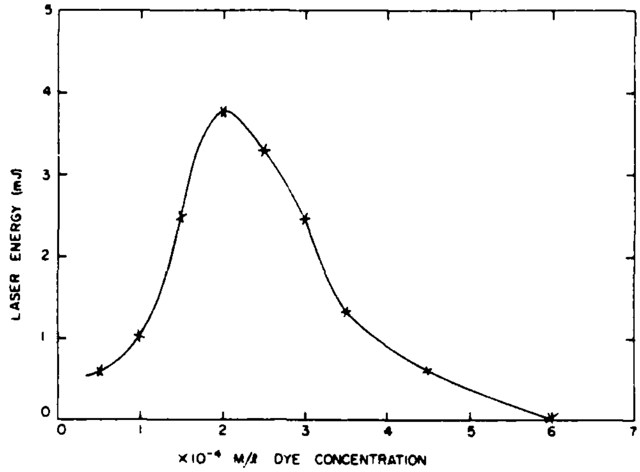

FIG. 21. Output dye laser energy from rhodamine 6G vs dye concentration, using 3.75 Torr of H_2 fill gas at 17 kV.

(triplet-triplet absorption) and higher population in the singlet states. The net result is an enhanced laser output power.

When measurements were made using N_2 gas at the fill pressure of 2 Torr and dye concentration of 1.2×10^{-4} M/ℓ, the results, as shown in Fig. 20, were very much different from those obtained with H_2. The overlap between the N_2 emission spectrum and the absorption spectrum of rhodamine 6G is considerably higher than for H_2 emission spectrum. The emission spectrum of N_2 thus allows for very efficient pumping even at a low-level dye concentration. When higher voltages were used, no improvement in the output laser power could be observed due to the saturation of the laser medium. The N_2 pumping light pulse, appearing in Fig. 16(b), shows that the rise time is relatively short for heavy molecules such as N_2. The reason for that is a faster ionization avalanche during discharge. Yet, the pulse duration is much longer than that of H_2 [Fig. 16(a)], and no pinching can be seen even at high voltages. Note that the H_2 pump pulse trace shows a sudden increase in the intensity due to the pinching plasma arriving at the central region of the HCP and thus that it can illuminate directly the photodiode PD 1 that is positioned along the HCP axis (Fig. 14). When higher dye concentration was used, the output laser power dropped rapidly. This may be due to a good match between the N_2 emission spectrum and the absorption spectrum of the dye, which causes the plasma light to excite only the surface layer of the laser medium.

In contrast, higher dye concentration produces higher laser output power when irradiated with the H_2 spectrum, which is UV enhanced. Measurement of the laser output power versus the capacitor bank voltage taken with D_2 fill gas yielded results very similar to those of H_2 at a pressure of 3.5 Torr.

5. Other parameters affecting laser output: Dye concentration and output mirror reflectivity

Figure 21 shows the dependence of the output laser energy on the dye concentration. Increase in the dye concentration makes available a larger number of molecules that can be excited, which results in a signal gain and an increase in the output power. Since the cavity loss remains constant, the ratio between the gain and loss also increases at higher concentration. The result is a superlinear increase in the laser output energy versus the dye concentration. According to Fig. 21, this effect persists up to the dye concentration of $\sim 1.5 \times 10^{-4}$ M/ℓ. Further increase in the dye concentration, however, results in concentration quenching. Namely, as the distance between two molecules decreases to ~10 nm or less, due to frequent molecular collisions, deexcitation takes place via nonradiative processes, thereby reducing the output laser energy. The optimum dye concentration that led to the peak laser energy was 2×10^{-4} M/ℓ when pumped with 3.75 Torr of H_2. No laser activity could be obtained at

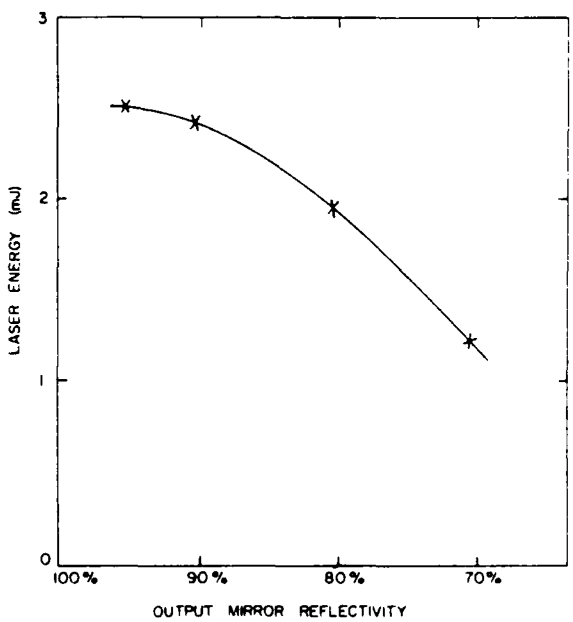

FIG. 22. Output dye laser energy vs output coupling, using 3.75 Torr of H_2 fill gas at 16 kV, and 2×10^{-4} M/ℓ rhodamine 6G dye.

dye concentrations above 6×10^{-4} M/ℓ.

Optimum system performance also requires maximization of the output coupling. The effect of this output coupling on the energy of the rhodamine 6G dye laser is shown in Fig. 22. The concentration of the dye was 2×10^{-4} M/ℓ, the fill gas was H_2 at 3.75 Torr, and the capacitor bank was at 16 kV. Optimum coupling was obtained at the output mirror reflectivity of 90%–95%.

C. Other observations and discussions

Shown in Fig. 23 are the dual oscillograms of the plasma and laser light pulses obtained, respectively, by the photodiodes PD 1 and PD 2 in Fig. 14, which reveal further information on the pumping light pulse. When a low pressure of 3–4 Torr of H_2 was used, the plasma pinch formed beyond the interelectrode space. The sudden rise in the plasma light intensity shown in Fig. 23(a) is due, therefore, to the plasma pinch column getting smaller than 2 in., the size of the hole at the center of the disk electrode. On the other hand, when a higher pressure, or a lower capacitor bank voltage was used, the plasma pinch, as indicated by Fig. 23(b), did not form beyond the interelectrode spacing indicating that the diameter of the plasma column was larger than 2 in.

Measuring the time durations of the different events recorded on the oscillograms—such as the time span for the plasma sheet to reach the electrode's enclosure, the rise time of the added spike on the plasma light pulse, and the delay time of the laser pulse—can reveal information: (1) the propagation velocity of the plasma sheet, (2) the plasma sheet thickness, and (3) the distance from the plasma sheet to the laser tube when the threshold condition for the laser action is obtained.

Figure 24 shows the traces of a pair of plasma and laser light pulses on the same time scale. Time t_1 is the propagating time of the plasma sheet inside the electrode enclosure (in the current design, 2 in. in diameter). Time t_2 is the time period over which the plasma sheet pinches to the open space along the center of the disk electrodes. Time t_3 is the time delay of the dye laser pulse. The average velocity v of the plasma sheet is

$$v \simeq \frac{2\ \text{in.}}{t_1} \simeq \frac{5.08\ \text{cm}}{3.8\ \mu\text{s}} \simeq 1.3 \cdot 10^{6}\ \text{cm/sec}.$$

The thickness of the plasma sheet must be smaller than $v \cdot t_2$, which is approximately 0.5 cm. The distance d between the plasma sheet and the laser tube when laser action takes place is 3 in.-$v \cdot t_3$, which is approximately 5 cm. These results are in agreement with the previously made observations.[1]

The distance d allows us to estimate the fraction of the plasma light that is utilized for laser pumping. The plasma sheet light can be analyzed as a superposition of point light sources. Considering the design of the plasma device, only about 1% of the actual pinch light was utilized for excitation of the laser medium.

For repetitive operation of the HCP dye laser system, dye circulation must be maintained so that the laser medium homogeneity may be preserved in the presence of the thermal heating created by the pumping pulse. However, circulation of the dye solution often introduces air bubbles within the solution. These air bubbles increase the dispersion of the propagating laser beam inside the laser medium, thereby reducing the laser output power. To reduce the amount of bubbles, an in-line Nupro filter (0.5 μm) was used. When the system was fired with a stationary, uniform dye solution, an improvement of 50% in the laser power output was ob-

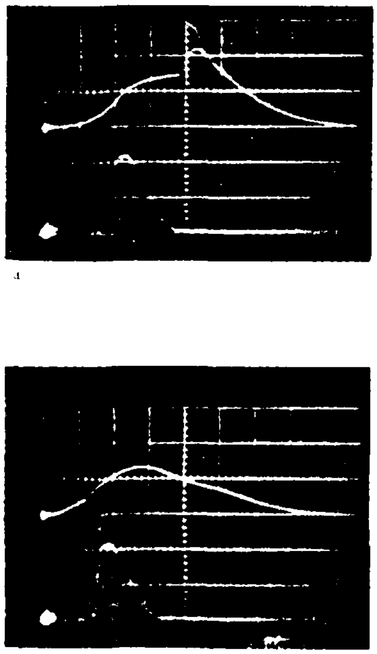

FIG. 23. Simultaneous oscillograms of the excitation light pulse (top) and the rhodamine 6G dye laser pulse (bottom). The vertical and horizontal axes, respectively, represent the light intensities in arbitrary units and the [illegible]. (a) Using 3.75 Torr of H fill gas. (b) Using 6 Torr of H fill gas.

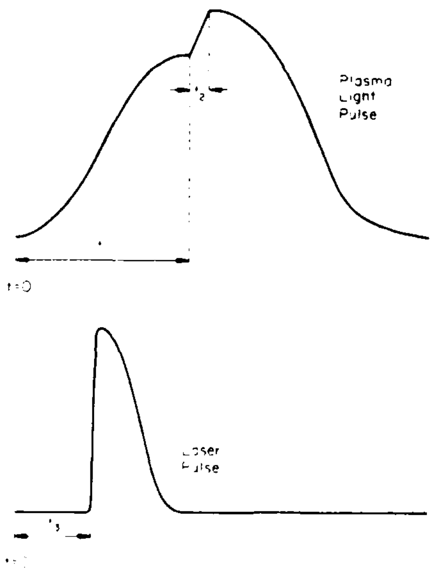

FIG. 24. Traces of plasma light and laser pulses.

tained. This indicates that intercavity loss due to the light dispersion created by the bubbles was significant.

Optimal performance of the system was obtained under the following conditions: (1) pyrex laser tube for rhodamine 6G, and quartz laser tube for coumarin dyes, with o.d./i.d.$\simeq n$, the index of refraction, (2) H_2 or D_2 gas fill at pressures of 3.5–4 Torr, (3) the capacitor bank voltage of 18 kV, (4) the dye concentration of 2×10^{-4} M/ℓ in reagent methanol, (5) output mirror reflectivity of 90%–95%, and (6) stationary and uniform dye solution. Under these conditions, output energy of ~ 10 mJ for a 1-μs laser pulse was obtained for rhodamine 6G, coumarin 480, coumarin 504, and LD 490. The volume of the laser medium was 5 cm^3.

As for the general lasing characteristics, the behavior of all the laser dyes tested in the present investigation was essentially the same. To be more specific, experiments, which led to the results contained in Figs. 19, 21, 22, and 23 for rhodamine 6G, were similarly repeated for coumarin 480, producing essentially the same results. (As indicated before, however, pyrex and quartz laser tubes of the same dimensions were used for rhodamine 6G and coumarin 480, respectively.) Coumarin 504 and LD 490 were also tested whenever deemed convenient, showing no visibly different behaviors. One can, therefore, safely conclude that for all practical purposes, the results of Figs. 19, 21, 22, and 23 can be regarded as if they are for coumarin 480, LD 490, or coumarin 504.

V. CONCLUSION

The performance of an array of dense plasma focuses having hypocycloidal pinch configuration has been evaluated as a new optical pump source for dye lasers. Using the plasma light, a variety of laser dyes was successfully pumped, which included rhodamine 6G, coumarin 480, coumarin 504, and LD 490. The maximum output energy and the duration of the laser pulses were, respectively, 10 mJ and 1 μs. The maximum output energy density of the lasing medium was 2 mJ/cm^3. Of particular significance was the fact that the output power of the coumarin 480 laser was as high as that of the rhodamine 6G laser, which is considered to be unattainable with the commercial Xe flashlamps since their UV output is not as strong as their visible output. It is an experimental proof that the present plasma light source is richer in UV than the commercial Xe flashlamps and that it is particularly suitable for pumping UV and blue-green laser dyes.

Although the work described in this report was mainly directed toward the pumping of dye lasers, the general properties and flexible features of the present plasma light source, which are briefly summarized in the following, should be applicable to the pumping of other lasing media, of which there are many. First, the plasma light pulse can be tailored to a desired shape with the proper choice of the gas species, of its fill pressure, and of the circuit parameters (such as the input energy, voltage, and inductance). Second, the all-metal construction of the plasma device allows for the input energies and thereby the resulting plasma light intensities to be much higher than that of the conventional flashlamps. Third, a good spectral match between the pump light and the lasing medium can be achieved by the choice of the fill gas species for the line spectrum and of its fill pressure for the controlled continuum spectrum. (However, an optimization is necessary since the gas species and the fill pressure also affect the shape of the plasma light pulse.) Fourth, due to the plasma pinch effect, the spectral width of the plasma light is much narrower than the Planckian spectrum, the photon flux at the lasing medium is extremely high, and the light spectrum is particularly rich in UV. Fifth, the length of the plasma light can easily be varied by stacking up fewer or more disk electrodes. Sixth, the operation and maintenance of the plasma device are, respectively, simple and minimal. Seventh, the lifetime of the plasma device is virtually unlimited. Eighth, although it has not yet been investigated, the repetitive operation of the device should pose no problem since its only limiting factor is the availability of a high-energy power supply capable of charging a capacitor bank at a fast pace. Finally, the superlinear dependence of the plasma light intensity on and the general performance improvement of the plasma device with the capacitor bank voltage appear to project a superb performance of the plasma device as a pump light source at the higher voltages. Because of these features characteristic of the device, it may be concluded that the current plasma pinch light source has the potential for becoming a most versatile optical pump for high-power lasers. That its fluorescent spectrum is rich in UV and VUV also indicates that the present light source is particularly suitable for pumping UV and blue-green lasers.

In addition to the dye lasers described in this work, atomic iodine and xenon recombination lasers have also been pumped by a plasma device similar to the present device.[6,7] However, the dye lasers have thus far produced the highest output power, which is approximately 10 kW. With a simple modification of the plasma device and the laser tube, the output power of these dye lasers should easily increase by a factor of 100.

On the negative side, the disk electrode configuration of the present plasma device does not allow for an easy installation of light reflectors which are essential in directing the available pump light toward the lasing medium. This means that if the high efficiency, not the high power, is the name of the game, then the current laser system might not fit into the game plan. Also, at higher voltages, as previously mentioned, the plasma-pinching action becomes stronger resulting in a pinched plasma column much higher in density and temperature but smaller in diameter. Presence of a laser tube along the axis of the plasma column could interfere with the plasma pinch formation at high voltages, which could result in the reduction of the laser output energy and of the laser tube lifetime. One easy way to avoid this problem is to increase the gas fill pressure, which will not only impede the plasma-pinching action, but also enhance the fluorescent output of the plasma. An increase in the gas fill pressure, however, often results in the increased rise time of the plasma light pulse, which in turn might become a hindrance when the sought-after laser action specifically calls for a short rise time of the pump light. For these reasons, it is expected that the present plasma system will find broad applications in those laser systems where the laser activities can

be achieved directly from the pinched plasma column, not from the lasing medium contained in a laser tube inserted along the axis of the plasma column.

As far as the application of the current plasma system as an optical pump for dye lasers, it must be pointed out that some of the limitations mentioned above could be overcome by yet another plasma compressor which, for example, would form the plasma pinch away from the laser tube. As a result, the new plasma compressor would be immune to damaging the laser tube at high voltages. We are currently in the process of testing a new laser system with a plasma compressor possessing these desirable features. Results from this investigation will be discussed in a future publication.

ACKNOWLEDGMENT

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B. Results from Mather-type Dense Plasma Focus

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Mather-type dense plasma focus as a new optical pump for short-wavelength high-power lasers

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For the first time, a Mather-type dense plasma focus (MDPF) is successfully operated as an optical pump for lasers. Rhodamine-6G dye is optically pumped using the MDPF fluorescence, producing a laser pulse 1 μs in duration and more than 50 kW in output power. No optimization is attempted either of the laser cavity or of the lasing medium concentration and volume. A brief description of the experimental setup is presented, along with a summary and discussion of the results. The advantages of the present optical pump source and, in particular, their implications for the pumping of short-wavelength lasers are discussed.

PACS numbers: 52.75. – d, 42.55.Mv, 42.65.Gv, 42.60.By

The term "plasma compressors," of which there are many, is loosely used to indicate a plasma device which is capable of producing a self-constricting plasma discharge with high electron densities and temperatures. The Mather-type dense plasma focus device (MDPF), which saw its birth around 1960[1,2] and which we are using in the present work, is one such plasma compressor.[3] As shown by Fig. 1 (which is the schematic of an MDPF-based optical pumping system), an MDPF device is a gas-filled cylinder consisting of two circularly symmetric metal electrodes separated at the breech by an insulator-vacuum seal. The cylinder is open at the muzzle for the emergence of plasma. A high-voltage, high-current power supply (in the present work, a capacitor bank) is connected across the electrodes at the breech. As the current is dumped into the system using a fast switch, breakdown occurs at the breech along the surface of the insulator. The resulting discharge current sheet is then accelerated, by the $\mathbf{J}\times\mathbf{B}$ force, toward the muzzle. At the end of the electrode, the plasma sheet symmetrically collapses toward the center axis, thus forming a very dense plasma focus. This plasma focus, which lasts approximately 100 ns, typically has electron densities greater than 10^{19} cm^{-3} and temperatures around 1–3 keV.[3] The plasma-pinching effect also creates an intense beam of charged particles ejected in both directions along the center axis. The beam impinging on the center electrode rapidly heats the interchangeable radiation source (Fig. 1) creating a very hot plasma, spectrally specific to the type of target material used. This second process lasts for several microseconds. The total fluorescence from the plasma device is very rich in UV, VUV, and some x-ray emission, thus rendering itself as a tunable pump light source for blue green, UV, and excimer lasers.

Using the fluorescent output of an MDPF, successful laser operation has, for the first time, been achieved. A schematic of the MDPF-based optical pumping system designed for the pumping of laser dyes is shown in Fig. 1. The bottom drawing of Fig. 1 is the side view of the system, showing the coaxial electrodes as the main component. A light reflector is also shown at the top of this figure along with the circular cross sections of the laser tube which in the present case is a dye cuvette. The light reflector is designed such that it may direct the plasma light toward the laser tubes. The top drawing of Fig. 1, which is the top view of the laser system, shows a laser resonator having four cavity arms in an open-ring configuration. The dark circular cross sections also seen at the center of the top drawing are the two coaxial electrodes. The dense plasma focus forms at the center of these electrodes, just above the interchangeable radiation target.

The capacitor bank was of 87.27-μF total capacitance and could safely be operated at up to 17 kV. The current was discharged into the coaxial electrodes through a spark-gap switch operated in air. The plasma chamber was first evacuated and then filled with 2–10 Torr of hydrogen gas. The

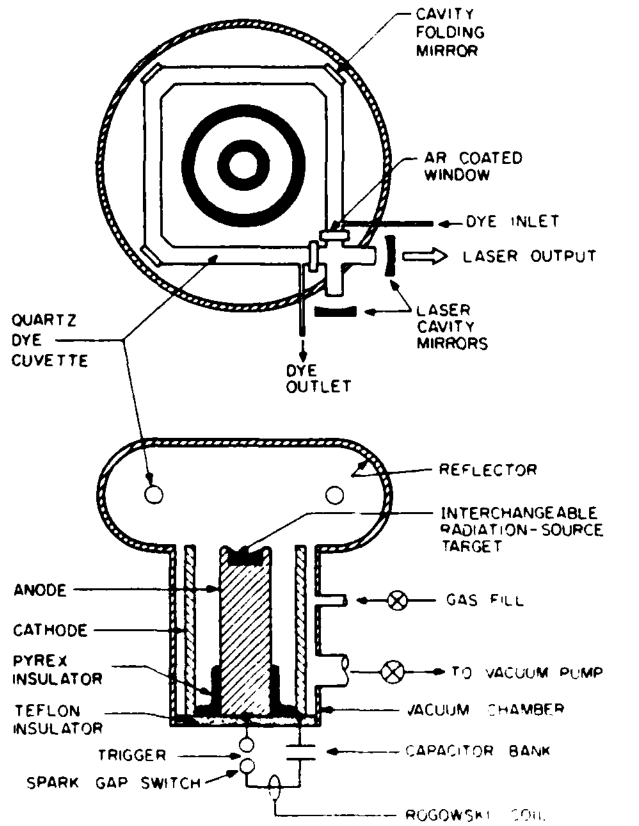

FIG. 1. Top and side views of the laser system which employs a Mather-type dense plasma focus as the excitation light source

radiation source at the top of the center electrode was made out of brass. The center electrode was positively pulsed.

The temporal behaviors of the current derivative, plasma pump light, and laser output pulse are shown, respectively, in the top, middle, and bottom traces of Fig. 2. The initial bank voltage was 17 kV and the gas fill was 2 Torr of hydrogen. The current derivative trace exhibits a sharp singularity near the 4-μs point, which indicates that the propagating plasma current sheet collapses into a dense plasma focus at that instant. The plasma pump light intensity trace is the temporal change in illumination as "seen" by the dye cuvette. (Pump light rise times could be varied from 0.2 to 1 μs.) The intensity variation of the resulting output laser pulse indicates that the laser activity is initiated at the 4.5-μs point and lasts only 1 μs, owing to the triplet quenching effects in the dye media. For a rhodamine-6G dye solution at 5×10^{-5} mol/ℓ in methanol and for a 20% cavity output coupling, laser energies of ~ 25 mJ per cm^3 of lasing medium were obtained.

The results indicate that at the time of lasing threshold, only 30% of the energy initially stored in the capacitor bank has been delivered into the MDPF, roughly 5 kJ. At the surface of the dye cuvette, the peak optical energy per unit area for the wavelengths between 200 nm and IR is measured to be 300 mJ/cm^2.

The spectral content of the MDPF pump consists of a continuum emission due to electron bremsstrahlung in the ion field. And, since the charged particles in the plasma move in a concerted manner due to the plasma-pinching action, the spectral width of the continuum emission is much narrower than that of a blackbody (usually one-fifth in width).[4] In the dense plasma focus the electron temperatures become very high extending the spectrum into the soft x-ray region. The quartz dye cuvette blocks out most radiation under 200 nm; therefore, the continuum spectrum usable for the lasing of dyes is from 200 to 400 nm. Superimposed on the continuum is the intense line spectra characteristic of the fill gas and target material. By proper choice of target material, these line radiations may be spectrally matched to the absorption band of the laser active media.

It must be emphasized that the performance of the MDPF pump light as described in this report in conjunction with the pumping of a laser dye should only be viewed as a demonstration of its potential as a new optical pump, but not as an illustration of its maximum capability as an optical pump source. Under the optimal conditions, the performance of the MDPF light source could very well be spectacular, especially at very high voltage ($\geq$20 kV) since the results thus far indicate that there is a superlinear relationship between the capacitor bank voltage and the output laser power.[5,6]

Finally, the advantages of the MDPF light are pointed out as compared to those for other plasma compressors, which have in recent years been successfully operated as optical pumps for lasers.[4,7,8] First, the MDPF light makes possible an easy installation of light reflectors which can efficiently direct the plasma light toward the lasing medium. Second, unlike the case of the hypocycloidal pinch,[7,8] there is no danger that the presence of the lasing medium will interfere with the plasma focus formation. Therefore, a longer lifetime is expected of the present laser system at high energies. Third, the x-ray output of the MDPF device is generally considered to be the highest of all the plasma compressors put to use as an optical pump. We are currently in the process of utilizing this short-wavelength output of the MDPF fluorescence for the optical pumping of short-wavelength lasers.

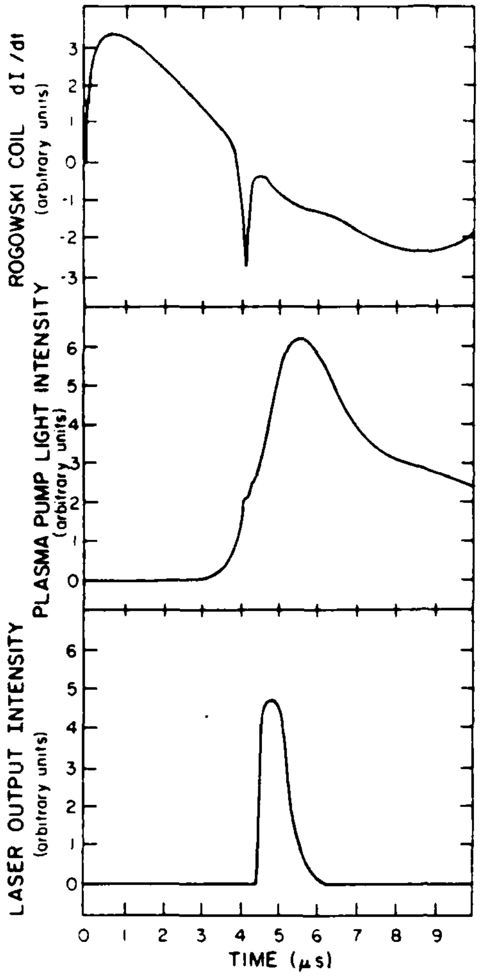

FIG. 2. Simultaneous oscilloscope traces representing the performance of the MDPF-based laser system.

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III. CONCLUSIONS

The performances of the two plasma focuses, hypocycloidal pinch (HCP) and Mather-type dense plasma focus (MDPF), were evaluated, respectively, as a new optical pump for lasers. A detailed study was carried out on the HCP-based optical pumping system successfully producing laser activities from a variety of organic dyes including rhodamine 6G, coumarin 480, coumarin 504, and LD 490. One of the significant findings of this study was that the output power of the coumarin 480 laser is as high as that of the rhodamine 6G laser. This cannot be achieved with commercial Xe flashlamps since their UV outputs are not as strong as their visible outputs. Thus, it is beyond any doubt that the HCP light source is richer in UV than the commercial Xe flashlamps UV and blue-green lasers.

An extensive luminescence characteristics study was carried out on the HCP plasma demonstrating its many attractive features as a high-energy short-wavelength optical pump: for example, the controllability of the plasma light brightness, rise time, and spectral contents. Based on the observations and the data from the lasing experiments, it is safely predicted that, with a simple modification of the HCP plasma device and the laser tube, laser output powers in excess of 1 MW should be easily achieved.

On the negative side, it was noted that the disk electrode configuration of the HCP device does not allow for an easy installation of light reflectors that can direct the available pump light toward the lasing medium. This prompted a search for an alternative plasma pinch configuration that will not only allow one to retain all the desirable features of HCP, but also facilitate implementation of light reflectors. The investigation into MDPF resulted from this search and led to the development of a new optical pump more powerful and flexible than HCP.

An MDPF-based optical pumping system was designed, constructed, and

successfully operated for the first time to produce laser activities. Rhodamine 6G dye was optically pumped using the MDPF luminescence, producing a laser pulse 1-μs in duration and more than 50 kW in output power. Considering the fact that *no optimization* was attempted either of the laser cavity or of the lasing medium concentration and volume, this proof-of-principle experiment is a clear indication that MDPF is superior to HCP as an optical pump and that there is not only room for improvement but, more importantly, there is a well-justified need that the MDPF device be researched further as a high-energy short-wavelength optical pump.

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